# BRL

REPORT NO. 1165
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AN APPLICATION OF THE JET-FORMATION THEORY TO

A 105MM SHAPED CHARGE

F. E. Allison
R. Vitali

# BALLISTIC RESEARCH LABORATORIES

# ABERDEEN PROVING GROUND, MARYLAND

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FEAllison/RVitali/iv
Aberdeen Proving Ground, Md.
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ABSTRACT

The equations describing the cone-collapse and jet-formation process
are shown to be in excellent agreement with the emerging-jet-velocity,
radioactive-tracer, and slug-recovery data for the 105mm unconfined test
charge. Because the number of parameters measured experimentally exceeds
the number needed to solve the equations, compatibility of the data with
the equations shows that the non-steady theory correctly describes the
formation of that portion of the jet able to penetrate mild steel.
A polynomial representation of the collapse velocity is obtained which
is believed sufficiently accurate for most problems requiring values for
this parameter.

# INTRODUCTION

This report presents numerical results from an accurate computation of the liner collapse velocity for a 105mm shaped charge. A drawing of the charge, together with a table of pertinent dimensions, is presented in Figure 1. In addition to obtaining values for the collapse velocity, it is also shown that the available data for this charge are compatible with the currently accepted theory of liner collapse and jet formation.

The first published theory describing the formation of a high-speed metallic jet by a lined-cavity charge appeared in the Journal of Applied Physics for June, 1948[1]. The mathematical description of the process was based on steady-state hydrodynamics and predicted the formation of a jet whose length was constant and equal to the slant height of the cone. There was, however, ample experimental evidence to show that jets formed by shaped charges contained a spectrum of velocities with the front of the jet traveling much faster than the rear. In order to describe the velocity gradient in the jet, Pugh[2] and his associates developed a more general theory of the jet-formation process. The generalized theory is based on the same steady-state hydrodynamic concepts as the original theory; however, the collapse velocities of the liner elements are no longer assumed to be the same for every element, but are allowed to vary according to the position of the liner element within the charge. The pertinent equations describing the collapse of a conical shaped-charge liner by a plane detonation wave propagating parallel to the axis of the charge are:[2]

$$\delta = \sin^{-1}(V_o/2U) \tag{1}$$

$$V_j = V_o \csc(\beta/2)\cos(\alpha + \delta - \beta/2) \tag{2}$$

$$dM_s/dM = \cos^2(\beta/2) \tag{3}$$

$$\tan\beta = \frac{\sin(\alpha + 2\delta) - x\sin\alpha\left[1 - \tan\delta\tan(\alpha + \delta)\right] V_o'/V_o}{\cos(\alpha + 2\delta) + x\sin\alpha\left[\tan(\alpha + \delta) + \tan\delta\right] V_o'/V_o} \tag{4}$$

where $\alpha$ is the half angle of the conical liner; $\delta$, the angle between
the direction an element of the liner travels after being struck by
the detonation wave and the normal to the surface of the liner; $V_o$,
the velocity at which the liner travels towards the axis; $V_j$, the
velocity of the jet element formed; $\beta$, the angle between the collapsing
liner wall and the axis; $M_s$, the mass of the slug; M, the mass of the
liner; and x, the initial axial coordinate of the liner element. Primed
quantities are obtained by differentiating with respect to x. The
velocity with which the detonation front sweeps along the liner surface
is designated by U. For a plane detonation front and a conical liner
$U = U_D/\cos\alpha$, where $U_D$ is the detonation velocity of the explosive.

Equations (1) to (4) represent four independent relations
involving the five unknown quantities, $M_s$, $\beta$, $V_j$, $V_o$, and $\delta$. In
principle, the experimental determination of any one of the quantities
is sufficient to provide a complete description of the process since
Equations (1) to (4) can then be solved for the remaining four quantities.
Furthermore, an experimental check on the accuracy of the theory can be
obtained by measuring any two of the five quantities. The qualitative
accuracy of the jet-formation theory was originally demonstrated[3] by
experimentally determining $\beta$ (x) and $V_j$(x). Experimental values for
$\beta$(x) were readily obtained from slug-recovery experiments using (3),
and $V_j$(x) was determined from emerging-jet-velocity and jet-collection
measurements. By subtracting the slug mass from the corresponding
liner mass, the cumulative mass of jet material $M_j$(x) was determined.
It was then possible to determine the value of x corresponding to a
given amount of penetration, x(P), by firing through targets of various
thickness and collecting the unused jet material. The velocity of the
impinging jet, $V_j$(P), was obtained as a function of penetration depth
by measuring the velocity of jets emerging from targets whose thicknesses
were varied. The jet velocity corresponding to the liner element located
at position x was then obtained by eliminating the penetration from the
two functions x(P) and $V_j$(P). The method of analyzing the data that
was used in the original verification of the jet-formation theory is

illustrated by the diagram shown in Figure 2. The general agreement between the $\beta$ calculated directly from slug-recovery data and the $\beta$ calculated from (4) showed the theory to be qualitatively correct.

It was recognized that the original study of the collapse process could be improved in at least two respects. First, the jet-collection experiment used in determining $V_j(x)$ was not as accurate as desired. Second, the method of analyzing the data required an experimental curve to be differentiated in order to determine $\beta(x)$, and these values for $\beta(x)$ were used to determine $V_o$. When (4) is finally used to compute new values of $\beta$ as a check on the validity of the theory, it is necessary to obtain the derivative of $V_o$. Obviously this involves terms containing the second derivative of the original experimental data. For this reason, there is some question concerning the numerical accuracy of this method for determining the compatibility of the experimental data with (1) to (4).

Eichelberger[4], in a later study of the problem, completely rejected the jet-collection data. He obtained $V_o$ by integrating (4) using experimental values of $\beta$ determined from new and more precise slug-recovery experiments. The values of $V_o$ and $\beta$ were used to compute the jet velocity from which it was possible to obtain the spatial position of the jet elements at any given instant of time. These results were then compared with experimental jet-velocity data in order to obtain a check on the accuracy of the theory. The largest source of uncertainty in this analysis arises from the difficulty in choosing the initial conditions for integrating (4).

Uncertainty in the $V_j(x)$ curve due to inaccuracies in the jet-collection experiment can be circumvented by a more precise experiment in which a radioactive tracer is plated on the inside surface of the liner. The first experiments with radioactive tracers[5] were no more precise than the original jet-collection experiments. However, it was apparent that the radioactive-tracer technique could be used to obtain reliable data for large caliber charges, such as the 105mm test charges used at the Ballistic Research Laboratories. During the past several

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years, complete data have been obtained for unconfined charges containing 105mm conical copper liners.  This report contains an analysis of the data obtained and represents a complete description of the collapse process for these charges.

## REDUCTION OF EXPERIMENTAL RESULTS

The penetration produced by a specific zonal element was determined by plating a band of $Ag^{110}$ on the inside surface of the liner[6]. $Ag^{110}$ was chosen because it is readily detected, giving off both strong gamma and high-energy beta radiation. The physical properties of $Ag^{110}$ are similar to those of copper and it possesses a conveniently long half-life (270 days). The 105mm charge produces a large hole in which the transportation of radioactive material from one part to another by succeeding portions of the jet is sufficiently small so that reproducible data can be obtained. The charges were encased in a 0.375 in. thick plastic body and fired from an 8.25 in. standoff into stacked 6.0 in. by 6.0 in. by 1.0 in. mild-steel plates. The results were sufficiently reproducible to determine the location of the penetration produced by the tagged jet element to within 0.50 inch. The experimental data were interpolated to obtain the penetration depths corresponding to values of x between 4.0 cm and 8.0 cm inclusive. Values of P were determined for every 0.5 cm change in x within this range and checked for numerical accuracy by inverse interpolation. The results are presented in Table I.

The emerging jet velocities were determined by firing the charges from an 8.25 in. standoff into targets whose thicknesses were varied systematically[7]. It should be noted that these charges were not encased in the light-weight plastic bodies used in the radioactive work. However, it was believed that the 0.375 in. plastic casing did not seriously alter the jet-formation process, and all the data were regarded as representative of the charge illustrated in Figure 1. The emerging jet velocities were determined using an oscilloscope and a system of grids, which measured the time required for the jet to travel between two known points in space. This technique for measuring the emerging jet velocities was chosen because it is possible to obtain reliable data at velocities below those for which optical methods can be used. The data obtained with the electronic system were checked

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against similar data obtained with a streak camera for those velocities where the optical techniques were applicable. The experimental data were interpolated to obtain jet velocities corresponding to penetration depths that were multiples of 1.0 in. or 2.54 cm. The results were smoothed slightly to eliminate fluctuations in the first differences and checked for numerical accuracy by inverse interpolation. The smoothed values of P and $V_j$, which were used to represent the emerging-jet-velocity data, are presented in Table II.

The slug mass produced by a liner section was determined by firing sectioned 105mm liners into water and recovering that portion of the slug corresponding to the pertinent liner section[7]. Two 105mm liners were cut at a known reference plane perpendicular to the cone axis. Two liners were used in order to compensate for the metal lost in the machining process. The upper section was weighed, and then the two sections were glued together. The charges were fired into a 10-in. gun barrel filled with water. Two recognizable slugs were recovered per shot, and the one corresponding to the upper section of the cone was weighed. This was done for a number of reference planes, yielding slug mass as a function of cone mass and, simultaneously, cone mass as a function of position along the cone axis. It should be noted that the light-weight plastic bodies previously mentioned were not used in the slug-recovery program.

The experimental data were interpolated to obtain numerical values of slug mass versus cone mass for equal intervals of the cone mass. The values were smoothed to eliminate fluctuations in the first differences and checked for numerical accuracy by inverse interpolation. Results are presented in Table III. The cone mass was also obtained for equal intervals of x in the range between 4.0 cm and 8.0 cm, checked by inverse interpolation, and presented in Table IV. Since the entire penetration is produced by jet elements originating between 4.0 cm and 8.0 cm from the apex of the liner, there is no reason to define the function outside this interval unless penetrations into lower strength materials are to be considered.

## DETERMINATION OF THE COLLAPSE VELOCITY

The non-steady theory of jet formation discussed in reference (2) assumes a plane detonation wave throughout the collapse process. This was a valid approximation at the time, as the charges were of considerable length. The experimental results analyzed here were obtained from short charges; hence, the plane-wave approximation is no longer valid. The theory has been generalized for the short-charge geometry by assuming a spherical detonation wave emerging from the point of initiation. The primary difference between the equations for a plane wave and those for point initiation is that U is no longer constant, but instead is given by the relation

$$U = U_D/\cos\gamma \tag{5}$$

where, for each point on the liner, $\gamma$ is the minimum angle between the normal to the spherical wave front and the cone wall at the intersection of the detonation wave and the cone wall. One now designates the position of the liner element as a function of time by cylindrical coordinates $r(t)$ and $z(t)$ and determines, as in reference (2), $\tan\beta$ by evaluating $(\partial r/\partial z)_t$ when the liner reaches the axis $(r = 0)$. Equation (4) becomes:

$$\tan\beta = \frac{\tan\alpha + T'V_0\cos A + x\,\tan\alpha(\delta'\tan A - V_0'/V_0) + T'V_0\cos A}{1 + x\,\tan\alpha\left[\delta' + (V_0'/V_0)\tan A\right] - T'V_0\sin A} \tag{6}$$

where $\delta' = \left[V_0'/V_0 - U'/U\right]\tan\delta$, $A = \alpha + \delta$, and $T(x)$ is the time at which the detonation wave reaches a position x on the liner.

The method of analysis is illustrated by the diagram in Figure 3. The slug-recovery data were differentiated once in order to obtain a first approximation for the collapse angle, $\beta(x)$. The radioactive-tracer and emerging-jet-velocity data were used to define an empirical $V_j(x)$. Estimates of the collapse velocity for the first portions of the jet were computed using (1) and (2). The values of the collapse

velocity scattered substantially due to fluctuations in the derivative of the slug-recovery data; however, a value between 0.20 cm/µsec and 0.21 cm/µsec was indicated for the collapse velocity corresponding to the tip of the jet: i.e., the liner element located at $x = 4.0$ cm. A value was chosen for the collapse velocity of the element located at $x = 4.0$ cm, and collapse velocities were computed for $x > 4.0$ cm by propagating the solution using the first two terms of a Taylor series; i.e.,

$$V_O(x + \Delta x) = V_O(1 + V_O' \Delta x / V_O). \tag{7}$$

To determine $V_O'/V_O$, (6) was solved for $V_O'/V_O$ and numerical values calculated using the approximate values of $\beta$ obtained from the slug-recovery data. At this point new values of $\beta$ were calculated by solving (1) and (2), using the empirical $V_j(x)$ curve. New values of $V_O$ were calculated using the new values of $\beta$ and the process repeated until no further change occurred in $\beta$. This part of the analysis is an iteration process and is designated in Figure 3 by the heavy arrows. The collapse angle calculated from the jet-velocity curve using the iteration process was brought into satisfactory agreement with the slug-recovery data by making minor adjustments in the value of $V_O$ corresponding to the tip of the jet.

A check on the numerical accuracy was made by fitting the resultant values of $V_O$ with a fourth-degree least-squares polynomial and computing $dM_s/dM$ and $V_j$. This revealed a systematic difference which was attributable to use of only two terms in the Taylor series. The error was six parts in the fourth figure at $x = 4.5$ cm and four parts in the third figure at $x = 8.0$ cm. These differences were sufficiently small to allow correction by a minor adjustment of the coefficients of the first two terms of the $V_O$ polynomial. The final results of the analysis are presented in Table V.

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When calculating the jet and slug parameters from the polynomial for $V_o$, it was noted that $V_o$ had to have four significant figures in order to obtain a reasonable reproduction of $V_j$ in the region 4.0 cm $\leq$ x $\leq$ 5.5 cm because the computed values of $V_j$ were quite sensitive to the derivative of $V_o$. Increased accuracy in the derivative of $V_o$ was achieved by computing the collapse velocity from the empirical $V_j(x)$ values and using the slug-recovery data only as a check on the final results. Of course, values of $V_o$ presented in Table V are not accurate to four significant figures because they are based on experimental data.

Graphical comparisons of the results of this analysis with the experimental data are shown in Figure 4 and Figure 5. Figure 4 compares $V_o$ calculated from the fourth-degree polynomial and the experimental values determined at Carnegie Institute of Technology*. The experimental values are questionable in the second figure; however, they serve to demonstrate that the polynomial for $V_o$ is qualitatively correct. Shown also in Figure 4 is a comparison between experimental values of $V_j$ and those calculated from the polynomial for $V_o$. The latter comparison demonstrates the accuracy with which the polynomial represents the original data.

The jet mass, as well as the jet velocity, is important in determining the diameter of the hole produced by the jet. It is therefore necessary that values of $M_j$ computed from the polynomial for $V_o$ be in accord with experimental observations. Figure 5 shows the excellent agreement between experimental values of $M_j$, which are plotted as open circles, and the $M_j$ versus M computed from the polynomial for $V_o$. It should be noted that $M_j$ is defined as $M - M_s$ and therefore includes approximately 4 g of liner material dispersed as fine particles ahead of the penetrating jet.

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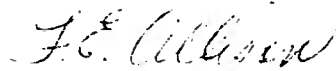
* R. W. Watson and K. R. Becker, Private Communication.

## CONCLUSIONS
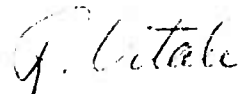
Although a large amount of shaped-charge research has been
completed, the collapse velocity remains a most difficult parameter
to determine accurately. Theoretical computations of $V_o$ have not been
refined to the point where they can be used without serious reservations.
Direct experimental observations have provided a few values of $V_o$, but
the numerical accuracy of these measurements is questionable in the
second figure. The systematic analysis of slug-recovery, emerging-
jet-velocity, and radioactive-tracer data is the only method for
obtaining accurate numerical values of $V_o$. The data obtained with
105mm unconfined test charges have been carefully analyzed and a
polynomial representation of the collapse velocity has been obtained.
Because the slug-recovery data were used only indirectly in determining
the polynomial for $V_o$, the excellent agreement illustrated in Figure 5
shows the non-steady theory of jet formation to be adequate for that
portion of the jet able to penetrate mild steel.

## ACKNOWLEDGEMENTS

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R. VITALI

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# TABLE I

Tabulated values of the penetration P as a function of the axial position x of the liner element producing the penetration. The tabulated values are based on radioactive-tracer data and the numerical accuracy is checked by inverse interpolation.

| x<br>cm | P<br>cm |
|---------|---------|
| 4.0 | 0.0 |
| 4.5 | 1.4 |
| 5.0 | 3.1 |
| 5.5 | 4.7 |
| 6.0 | 7.4 |
| 6.5 | 12.3 |
| 7.0 | 20.9 |
| 7.5 | 34.6 |
| 8.0 | 41.2 |

| | Original Data | | Inverse Interpolation |
|---|---|---|---|
| x<br>cm | P<br>cm | | P<br>cm |
| 4.32 | 0.6 | | 0.6 |
| 5.59 | 5.1 | | 5.1 |
| 6.86 | 17.8 | | 17.8 |
| 7.66 | 38.1 | | 37.2 |
| 8.47 | 42.5 | | 42.4 |

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## TABLE II

Tabulated values of the impinging jet velocity $V_j$ as a function of the penetration depth P. The tabulated values are based on emerging-jet-velocity data and the numerical accuracy is checked by inverse interpolation.

### Emerging Jet Velocity

| P<br>cm | $V_j$<br>cm/$\mu$-sec |
|---------|------------------------|
| 0 | 0.701 |
| 2.54 | 0.647 |
| 5.08 | 0.601 |
| 7.62 | 0.560 |
| 10.16 | 0.524 |
| 12.70 | 0.491 |
| 15.24 | 0.461 |
| 17.78 | 0.434 |
| 20.32 | 0.409 |
| 22.86 | 0.387 |
| 25.40 | 0.368 |
| 27.94 | 0.349 |
| 30.48 | 0.330 |
| 33.02 | 0.311 |
| 35.56 | 0.293 |
| 38.10 | 0.276 |
| 40.64 | 0.261 |
| 43.18 | 0.245 |

| | Original Data | Inverse Interpolation |
|---------|---------------|-----------------------|
| P<br>cm | $V_j$<br>cm/$\mu$-sec | $V_j$<br>cm/$\mu$-sec |
| 0 | 0.701 | 0.701 |
| 2.54 | 0.643 | 0.647 |
| 5.08 | 0.601 | 0.601 |
| 10.16 | 0.523 | 0.524 |
| 15.24 | 0.462 | 0.461 |
| 20.32 | 0.408 | 0.409 |
| 27.94 | 0.350 | 0.349 |
| 35.56 | 0.293 | 0.293 |
| 43.18 | 0.245 | 0.245 |

# TABLE III

Tabulated values of the cumulative slug mass as a function of
cumulative cone mass. The tabulated values are based on slug-
recovery data and the numerical accuracy is checked by inverse
interpolation.

| Cone Mass g | Slug Mass g |
|---|---|
| 0 | 0.0 |
| 10 | 9.3 |
| 20 | 18.6 |
| 30 | 27.8 |
| 40 | 37.0 |
| 50 | 46.2 |
| 60 | 55.4 |
| 70 | 64.6 |
| 80 | 73.7 |
| 90 | 82.6 |
| 100 | 91.5 |
| 110 | 100.4 |
| 120 | 109.3 |
| 130 | 118.0 |
| 140 | 126.5 |
| 150 | 134.8 |
| 160 | 142.8 |
| 170 | 150.4 |
| 180 | 157.7 |
| 190 | 164.7 |
| 200 | 171.5 |
| 210 | 178.3 |
| 220 | 185.0 |

| Original Data | | Inverse Interpolation |
|---|---|---|
| Cone Mass g | Slug Mass g | Slug Mass g |
| 20.6 | 19.1 | 19.2 |
| 41.7 | 38.7 | 38.6 |
| 69.9 | 64.6 | 64.5 |
| 103.1 | 94.3 | 94.3 |
| 122.9 | 112.0 | 111.8 |
| 142.1 | 127.9 | 128.2 |
| 166.3 | 147.7 | 147.6 |
| 188.9 | 163.9 | 163.9 |
| 213.6 | 180.5 | 180.7 |

## TABLE IV

Tabulated values of cumulative cone mass as a function of the axial coordinate measured from the virtual apex of the liner.  The tabulated values are based on slug-recovery data and the numerical accuracy is checked by inverse interpolation.

| x<br>cm | M<br>g |
|---|---|
| 4.0 | 51.7 |
| 4.5 | 65.8 |
| 5.0 | 81.7 |
| 5.5 | 98.3 |
| 6.0 | 117.2 |
| 6.5 | 136.7 |
| 7.0 | 159.3 |
| 7.5 | 182.1 |
| 8.0 | 206.1 |

| Original Data | | Inverse Interpolation |
|---|---|---|
| x<br>cm | M<br>g | M<br>g |
| 4.645 | 69.93 | 70.21 |
| 5.645 | 103.13 | 103.52 |
| 6.149 | 122.90 | 123.04 |
| 6.639 | 142.10 | 142.65 |
| 7.146 | 166.33 | 166.07 |
| 7.653 | 188.87 | 189.20 |

## TABLE V

Tabulated values of the jet and slug parameters computed from the fourth-degree polynomial representation of the collapse velocity.

| x cm | $V_o$ cm/$\mu$-sec | $V_j$ cm/$\mu$-sec | $dM_s/dM$ |
|---|---|---|---|
| 4.0 | 0.2050* | 0.712 | 0.921 |
| 4.5 | 0.2069 | 0.668 | 0.907 |
| 5.0 | 0.2065 | 0.635 | 0.897 |
| 5.5 | 0.2046 | 0.603 | 0.888 |
| 6.0 | 0.2013 | 0.562 | 0.874 |
| 6.5 | 0.1958 | 0.501 | 0.848 |
| 7.0 | 0.1870 | 0.417 | 0.799 |
| 7.5 | 0.1729 | 0.319 | 0.709 |
| 8.0 | 0.1509 | 0.225 | 0.578 |

$$* \quad V_o = -0.197898 + 0.288477x - 0.0775152x^2 + 0.00942615x^3$$
$$-0.000445364x^4 \qquad \text{for } 4.0 \text{ cm} \leq x \leq 8.0\text{cm}$$

M36AI ELECTRIC
DETONATOR

TETRYLBOOSTER
PELLET

COMPOSITION B

COPPER LINER

α = 21°

| DIMENSIONS | |
|---|---|
| A | 3.25" |
| B | 3.40" |
| C | 6.00" |
| D | 0.106" |
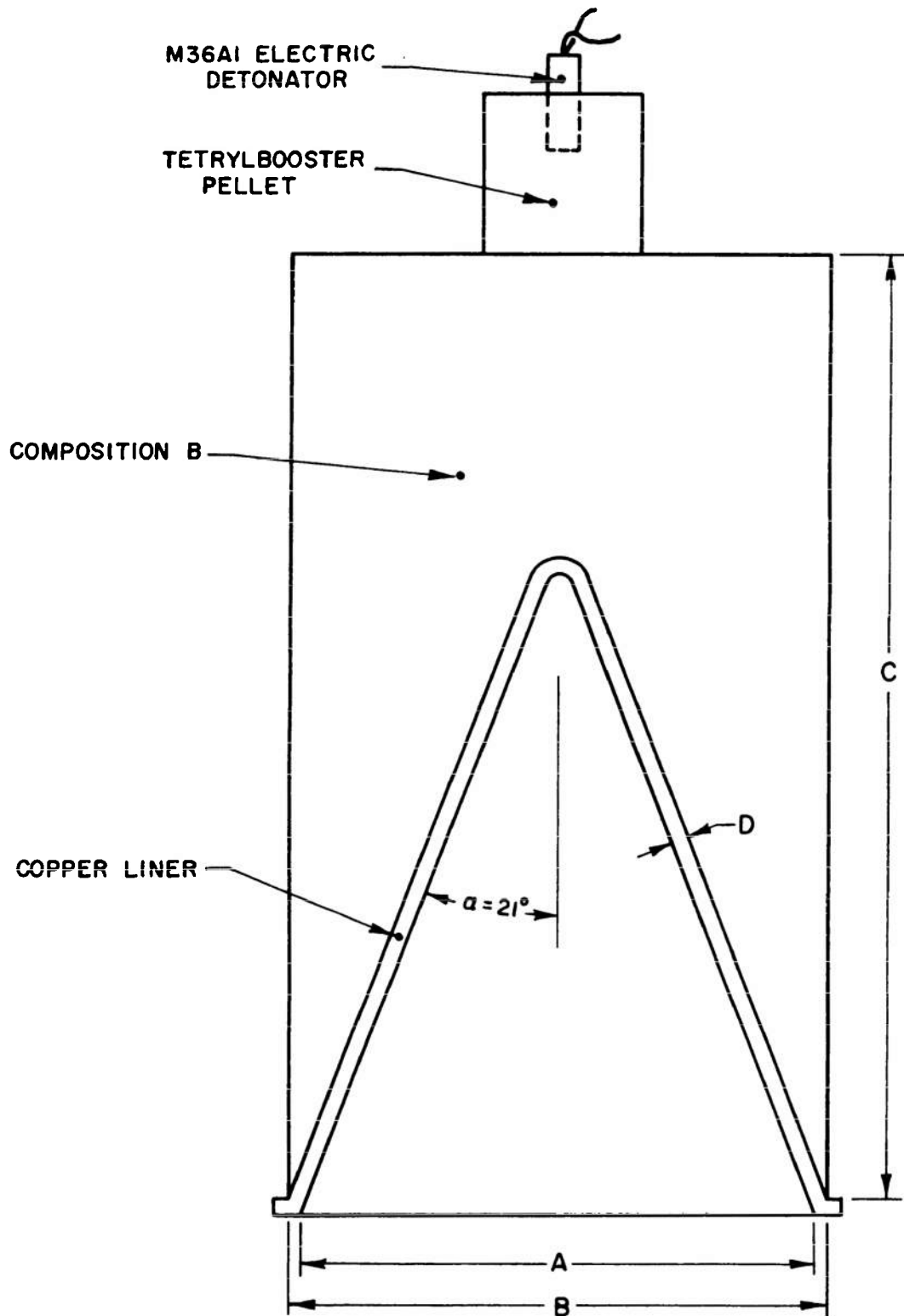
Figure 1: The 105mm unconfined test charge used
at the Ballistic Research Laboratories. Pertinent
dimensions are shown in the table.

SLUG
RECOVERY
DATA

$M_s = M_s(M)$

$M = M(x)$

$M_j = M - M_s$

$M_j = M_j(x)$

JET
COLLECTION
DATA

$P = P(M_j)$

EMERGING
JET VELOCITY
DATA

$V_j = V_j(P)$

$\dfrac{dM_s}{dM} = \cos^2\left(\dfrac{\beta}{2}\right)$

$\beta(x)$

(CHECK ?)

$V_j(x)$

$V_o = \dfrac{V_j \sin(\beta/2)}{\cos(A - \beta/2)}$

$A = a + \delta$

$\delta = \sin^{-1}(v_o/2U)$

$\tan\beta = \dfrac{\sin(a+2\delta) - x\sin a\left[1 - \tan\delta\,\tan(a+\delta)\right]v_o'/v_o}{\cos(a+2\delta) + x\sin a\left[\tan(a+\delta) + \tan\delta\right]v_o'/v_o}$

$V_o(x)$

$V_o'(x)$

$\delta(x)$
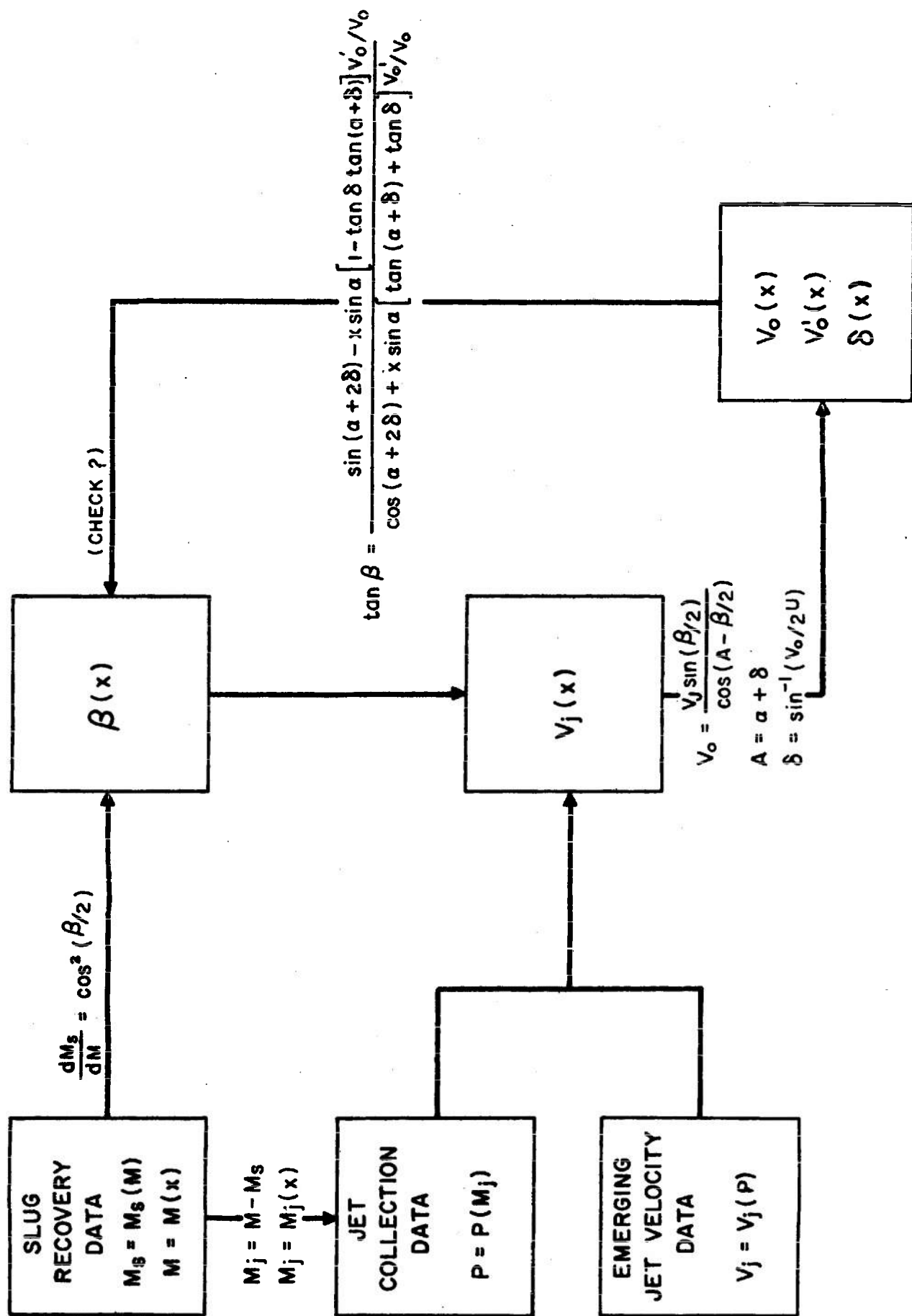
Figure 2: The method used to analyze the slug-
recovery and jet-collection data.

SLUG
RECOVERY
DATA

$M_S = M_S(M)$

$M = M(x)$

$\left(\begin{array}{l}\text{INITIAL CONDITION AND FIRST}\\ \text{APPROXIMATION FOR } \beta \text{ USED IN}\\ \text{CLOSED LOOP SOLUTION.}\end{array}\right)$

$\dfrac{dM_S}{dM} = Cos^2\left(\beta/2\right)$

$\beta(x)$

(CHECK ?)

$$\frac{V_o'}{V_o} = \frac{Tan\,a - Tan\,\beta + T'V_o\,(Cos\,A + Tan\,\beta\,Sin\,A) + x\,Tan\,a\,Tan\,\delta\,(Tan\,\beta - Tan\,A)\,U'/U}{x\,Tan\,a\,(1 + Tan\,\delta\,Tan\,\beta + Tan\,A\,Tan\,\beta - Tan\,A\,Tan\,\delta)}$$

$V_o(x)$

EMERGING
JET VELOCITY
DATA

$V_j = V_j(P)$

RADIOACTIVE
TRACER
DATA

$P = P(x)$

$V_j(x)$

$V_j = \dfrac{V_o\,Cos\,(A - \beta/2)}{Sin\,(\beta/2)}$

$\delta = Sin^{-1}(V_o/2U)$

$A = a + \delta$

$\beta(x)$

NOTE: ⇒ INDICATES CLOSED LOOP ITERATION USED IN OBTAINING VALUES OF $V_o(x)$ AND $\beta(x)$ CONSISTENT WITH EXPERIMENTALLY DETERMINED $V_j(x)$.
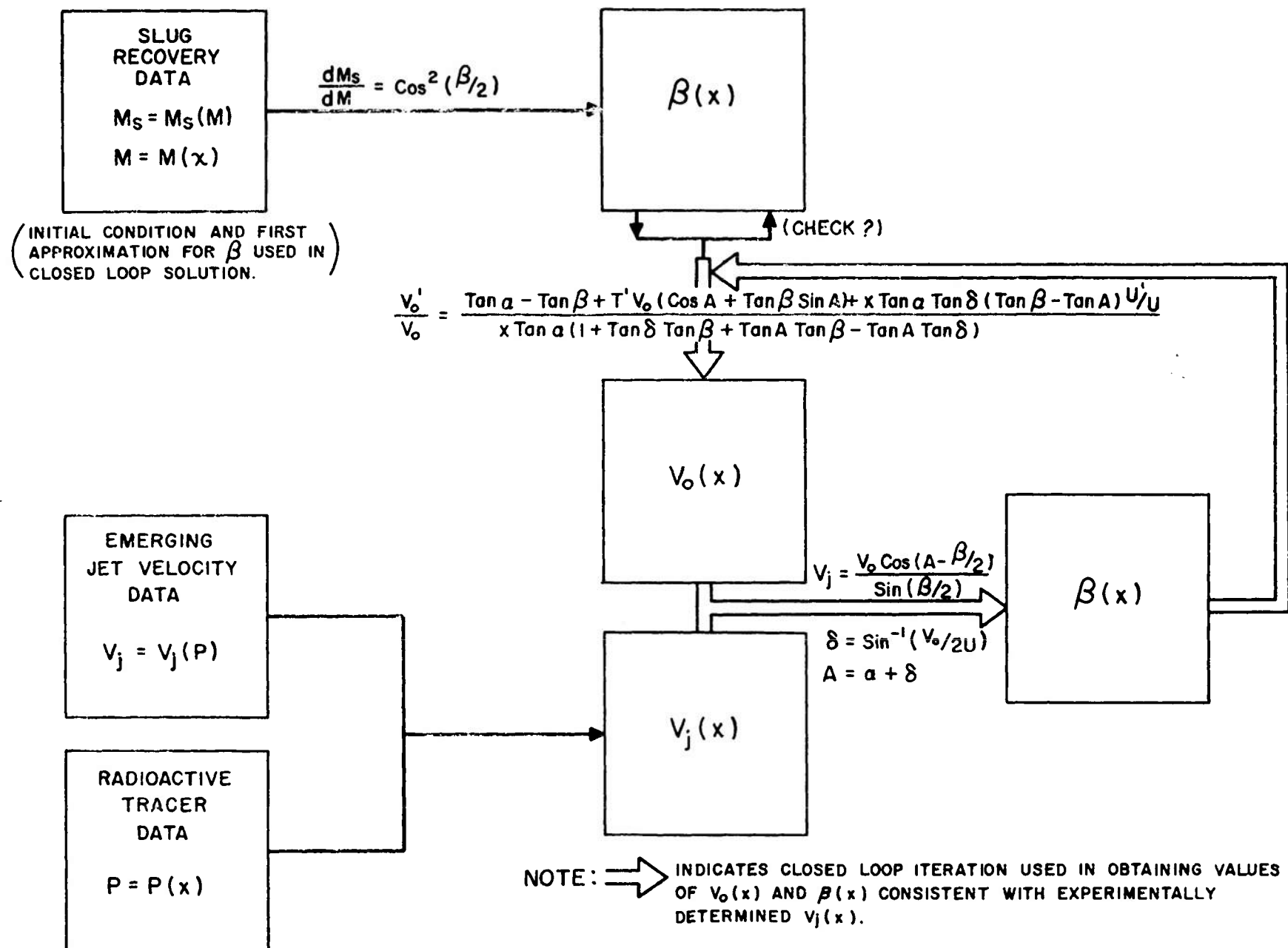
Figure 3: Method used to analyze the data obtained
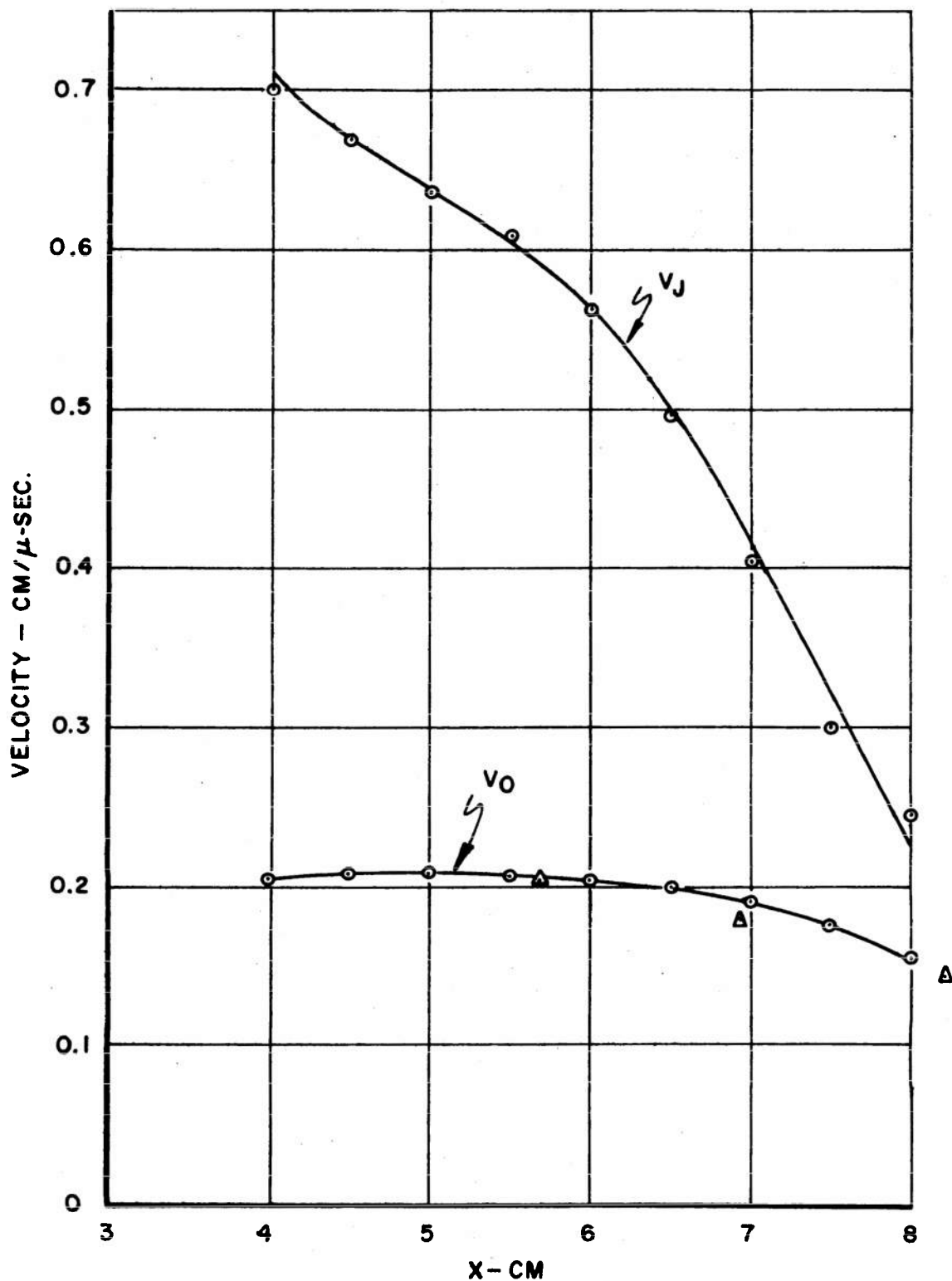with the 105mm unconfined charge.

Figure 4:  Results obtained from an analysis of the emerging-jet-velocity and
radioactive-tracer data for the 105mm unconfined shaped charge.  The open
circles represent results obtained from a numerical analysis of the data,
the triangles represent experimental values obtained at C. I. T., and the curves
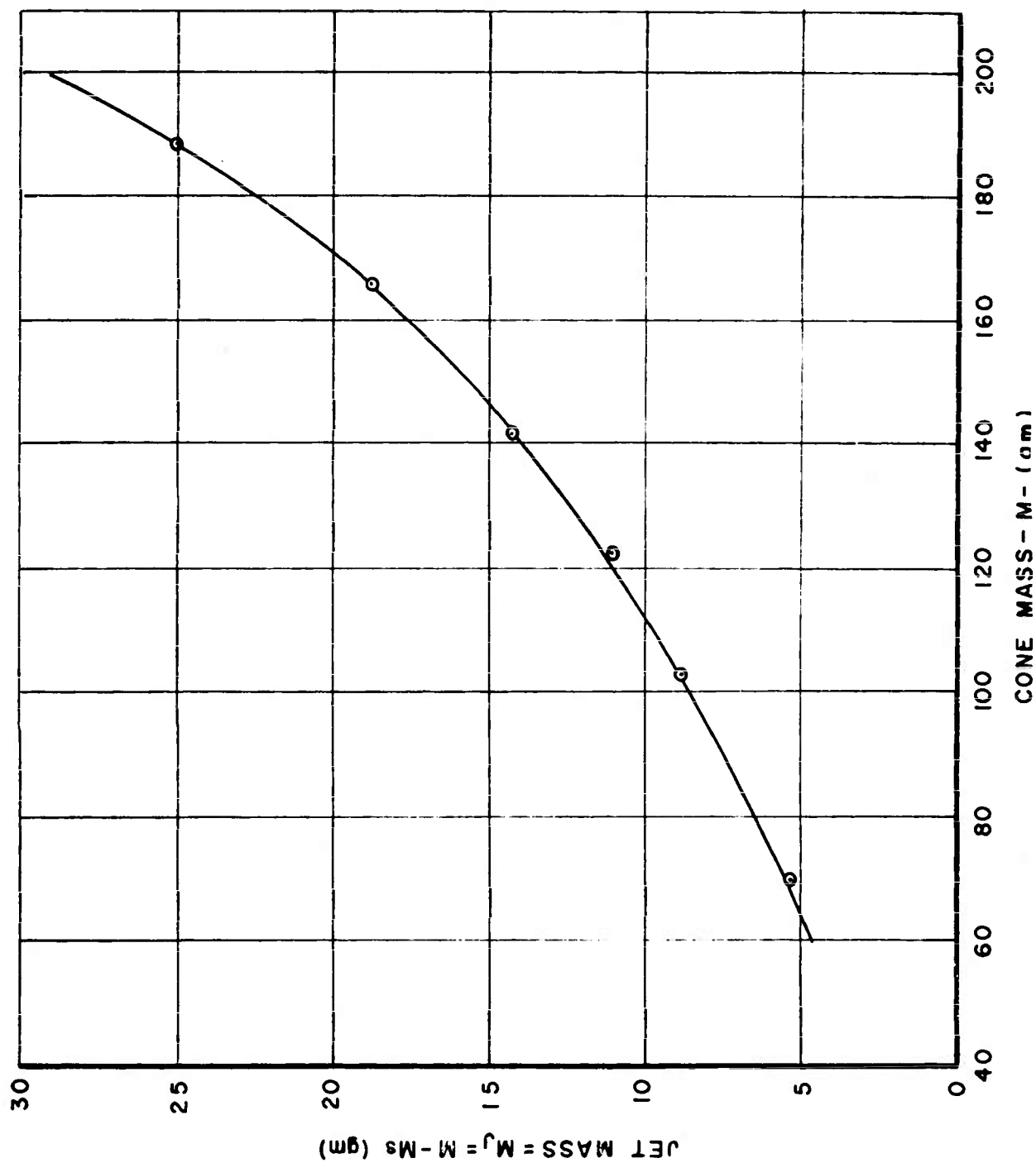represent values computed from a polynomial fit to $V_o$.

Figure 2: Results obtained from an analysis of the slug-recovery data for the 105mm unconfined charge. The open circles represent results obtained from a numerical analysis of the data, and the curve represents values computed from a polynomial fit to $V_o$.

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